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THE EFFECT OF VARYING SPATIAL FREQUENCY ON VISIBLE PERSISTENCE IN A TEMPORAL INTEGRATION TASK

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "The effect of varying spatial frequency on visible persistence in a temporal integration task" submitted by Evanne Joan Woods in partial fulfilment of the requirements for the degree of Master of Science.

Abstract

This study investigated the effects of varying spatial frequency content on visible persistence. The concept of sustained and transient channels has had heuristic value in the investigation of the mechanisms underlying persistence. Due to the response characteristics of these channels to different ranges of spatial frequencies, it was expected that a reduction of high spatial frequencies in the visual display would reduce the persistence of that display. The results of this study clearly confirmed this expectation. When the high frequency content of a display was reduced by defocusing, the persistence of the display, as measured by a temporal integration task, was reduced. Possible physiological mechanisms underlying these results were discussed in light of a channel model proposed by Breitmeyer and Ganz (1976).

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This study investigates the effects of varying spatial frequency on the visible persistence of a display.

Neurophysiological studies have demonstrated that it is possible to categorize the majority of retinal ganglion cells in the cat into two groups. These classifications are made on the basis of a number of characteristics revealed by recording techniques. One category, known as X-cells, is characterized as having slow conduction velocity and small, well-defined receptive fields (Enroth-Cugell & Robson, 1966; Cleland, Dubin & Levick, 1971; Hoffman & Stone, 1971). These X-cells are also known to respond well to high spatial frequencies and steady stimulation (Enroth-Cugell & Robson, 1966). In addition, when these cells are stimulated by a steady test-spot, they respond continuously from onset to offset of the stimulus. Because of this characteristic, these cells became known as sustained cells (Cleland et al., 1971; Ikeda & Wright, 1972). The same group of researchers have defined the other category of cells, known as Y-cells, as having rapid conduction velocities, and large, poorly defined receptive fields. These cells have been found to be most sensitive to low spatial frequencies and respond best to intermittent stimulation. When presented with a steady spot of light, the Y-cells respond with a brief burst of activity to onset or offset of the stimulus. For this reason, they became known as transient cells.

While the initial work was done with cats, the existence of sustained and transient cells has been confirmed in several primate species (Gouras, 1969; Marrocco, 1976). It now appears likely that cells with the same properties exist in the human visual system. Psychophysicists

have investigated the relative contributions of sustained and transient activity in the human visual response by manipulating two variables: spatial and temporal frequency.

Sustained and Transient Channels

Using stimuli which varied in spatial frequency, Keesey (1972) and Tolhurst (1973) probed the visual system's capacity to detect rapid changes in time. Their work demonstrated a clear distinction between the detection of pattern and the detection of flicker. Pattern was detected best when stimuli were presented steadily or at low temporal frequencies, while flicker detection was best when low spatial frequency stimuli were used. These results suggest the existence of two separate channels for the processing of visual information: one that is responsive to high spatial frequency and low temporal frequency (pattern detection system), and one that responds to low spatial frequency and high temporal frequency (flicker detection system).

The suggestion that these two channels might have the same characteristics as the sustained and transient cells was tested by Kulikowski and Tolhurst (1973). They predicted that transient activity would be greater for a grating that was alternated in phase than for the same grating simply turned on and off. They also predicted that sustained activity would not show this difference. Therefore, if the flicker detection threshold reflects transient activity, then it should be enhanced by the presentation of spatial frequency grating alternating in phase. The pattern detection threshold should be the same for both modes of presentation. Their results confirmed their predictions. Flicker detection was enhanced by the alternating of the grating, while pattern detection was the same for both the on-off and alternating

conditions. The enhancement of sensitivity to flicker found in this experiment reveals the psychophysical connection between flicker detection and transient activity and pattern recognition and sustained activity. This work resulted in the general use of the concept of sustained and transient processing channels in psychophysical research.

Temporal Characteristics of Processing within Channels

Further investigations have confirmed that sustained channels are sensitive to high spatial frequency and low temporal frequency, while transient channels respond best to low spatial frequency and high rates of temporal modulation. Breitmeyer and Julez (1975) found that contrast sensitivity for low spatial frequency could be enhanced by using stimuli with abrupt onset as opposed to a gradual onset. The type of onset did not make any difference in sensitivity for spatial frequencies above five cycles per degree (c/d). Tolhurst (1975) used long conditioning flashes of subthreshold gratings to show that sensitivity for short grating flashes could be enhanced or inhibited according to the phase relation of the flashes. He found that if he used a two c/d grating for both the test and conditioning flash, the shape of the relative sensitivity function showed a large transient component. When he used a 7.6 c/d grating, this transient component was not apparent in the relative sensitivity function. Both these studies show that the effect of sustained and transient activity can be separated out in psychophysical experiments. However, recent research has revealed much more about the temporal characteristics of the two types of channels than was apparent from the neurophysiological work. The capacity of the transient channels to respond to rapid change and the sustained channels' inability to do so led Breitmeyer to suggest that there might be a difference in the two

channels' integration time. That is, transient channels may process visual information more rapidly and in smaller chunks of time. This would allow these channels to respond to rapid changes in visual stimulation. A hint of this is provided in Breitmeyer and Julez's study cited above. The fact that transient channels respond better to abrupt onset than do sustained channels might lead one to suspect that transient channels are processing information in small enough chunks to "notice" the difference between an abrupt onset and a gradual one. The ramp time in Breitmeyer and Julez's study was 200 msec. Thus, to the sustained channels, a change occurring in a matter of one to two milliseconds is the same as a change occurring in 200 msec.

Breitmeyer (1975) pursued this idea in a simple reaction-time study. He demonstrated that the reaction-time for the detection of gratings increased gradually from 200 msec for a spatial frequency of 0.5 c/d to 350 msec for 16 c/d. The same relationship was apparent in Vassilev and Mitov's (1976) choice reaction-time data for both equal contrast and equal contrast sensitivity gratings. These authors also investigated backward masking and found masking at longer stimulus-onset-asynchronies (SOAs) when a low frequency masked a high frequency than visa versa. This provided support for the hypothesis that low frequencies are more rapidly processed than high frequencies.

The difference in the integration time of the two types of channels was further analyzed in studies that investigated the effect of the duration of a brief stimulus on the threshold of detection. Work by Nachmias (1967) and Arend (1976) showed that thresholds for briefly flashed high frequency gratings could be decreased by lengthening the pulse duration beyond 50 msec, while this same increase in duration had

no effect on the sensitivity for low frequencies. Breitmeyer and Ganz (1977) investigated this relationship between duration and contrast sensitivity over a number of spatial frequencies. Their results show that, for each frequency, sensitivity could be increased by increasing the duration up to a critical point. Beyond this point, a further increase in duration had no effect on sensitivity. This critical duration increased with spatial frequency, from 60 msec at 0.5 c/d to 200 msec at 16 c/d. This suggests, as Breitmeyer and Ganz point out, that the integration times for the low and high frequency channels are different. In other words, visual information that comes in within 200 msec is integrated in the high frequency channels, while the low frequency channels can only integrate information presented within 60 msec.

Visible Persistence

With the suggestion of differing integration times, the concept of sustained and transient channels has become important for researchers investigating visible persistence in information processing. Much of what is currently referred to as active integration in the visual system was earlier considered to represent the more passive characteristic of "persistence". The appearance of a continuous circle when a hot coal is whirled at the end of a string was regarded by Plateau as demonstrating that sensations may persist longer than the eliciting stimuli (Boynton, 1972). More empirically, Dunlap (1915) found that two pulses of light separated by as much as 50 msec were indistinguishable from two pulses presented in immediate succession. Erlanger and Gasser (1937) discussed such persistence effects in terms of the dispersion of afferent activity which results from different axon conduction velocities and synaptic latencies.

More recently, persistence has referred to a more specific hypothesis concerning visual processing and iconic memory. Sperling (1960) and Neisser (1967) used the method of partial report to reveal a large capacity, short-term visual store which preceded a limited capacity short-term memory. From the characteristics of the store, it was suggested that visual memory was in fact some kind of faithful representation of the stimulus that was available to the observer for several hundred milliseconds following a brief visual display. Neisser called this an icon or the iconic store. This concept implies that, when a brief stimulus is presented, a visible impression of the stimulus exists within the visual system for some time after the offset of the display. It also implies that when two stimulus displays are presented in succession, the visual information from the second display will become integrated with that from the first, if the second display occurs before the visible persistence of the first has faded. These suggestions were confirmed in many different ways, using masking paradigms and perceptual integration tasks (see Kahneman, 1968; Turvey, 1973; Coltheart, in press). But what in fact is persistence? A number of authors have suggested that the results of these studies might be explained by assuming that the visual system chunks incoming information into discrete bundles of time (perceptual moment hypothesis: Allport, 1968; Kristofferson, 1967; Haber & Hershenson, 1973). However, this does not really tell us how persistence is achieved within the physiological system. An alternative hypothesis has been presented that postulates a visible persistence based on the time required to process information within the visual system. This explanation of visible persistence has received more support from both the information processing literature and the neurophysiological

research (see Coltheart, in press; also Di Lollo, in press (a)). In fact Di Lollo has demonstrated that persistence of a display can actually fade before the offset of the display. This suggests that once processing is finished, persistence is finished.

A distinction must be made between the concept of visible persistence and visual persistence. Coltheart (in press) uses the term visual persistence to refer to iconic memory as a whole. According to his definition, visible persistence refers to that part of the icon which is in fact visible. On this view, visible persistence is a measure of the duration of visual processing for the visible portion of iconic storage. Since temporal integration paradigms normally require subjects to make a decision on the basis of the visible display, it is clear that it is visible persistence that is of concern here.

Many different paradigms are now used to investigate visible persistence. These are described extensively by Coltheart in his recent review of the area (in press). Efron (1970a,b,c), Haber and Standing (1970) and Bowen, Pola and Matin (1974) are all examples of studies employing judgements of synchrony. Here, subjects were asked to set the onset or offset of a probe stimulus to the offset or onset of a brief test stimulus. Other authors have compared the reaction-times to onset and offset of a test stimulus (e.g., Briggs & Kinsbourne, 1972) to get an estimate of perceived duration. Methods requiring the integration of information have also been used. These include the stroboscopic illumination of a moving stimulus (Allport, 1970) and the moving slit procedure (Haber & Standing, 1969). Another variation of the integrative technique originated with Eriksen and Collins (1967, 1968), and was further developed by Hogben and Di Lollo (1974). This method involved

the presentation of a display in discontinuous parts. The experimental task required that subjects be able to integrate the two parts of the display into a whole form. The important difference in this technique is that the subject is not required to make a judgement about discontinuity or duration. He is only required to make use of the visible information available to perform a recognition or location task.

Visible Persistence and Spatial Frequency

All of these studies, while revealing different estimates of visible persistence, have shown that persistence of a display beyond its offset varies inversely with duration up to a critical point. Most have also demonstrated an inverse relationship between intensity and persistence. An example of these relationships is given in Efron's work (1970a,b,c). Efron used judgements of synchrony to measure the duration of persistence. He asked subjects to pair the apparent offset of a spot of light displayed foveally or parafoveally to either the onset of a tone or the onset of a visual probe. He found that, as he increased the duration of the stimulus, the visible persistence beyond the stimulus offset decreased until the stimulus duration reached 130 msec. After this point, persistence remained constant as duration increased. The relationship between duration and persistence was such that, added together, they always equalled a constant for stimuli of 130 msec or less. This means that the perceived duration of very brief stimuli (below 130 msec) was always the same minimum value for a given intensity, irrespective of the actual duration of the stimulus. This minimum value was in fact the critical duration. It should be remembered that Breitmeyer and Ganz (1977) also measured critical duration in their study of thresholds for gratings. Their data functions for threshold enhancement over duration

for various spatial frequencies were very similar to those plotted by Efron in the studies described above. However, in the case of Breitmeyer and Ganz, critical duration was found to vary as a function of spatial frequency. As was previously noted, this work, in conjunction with other studies, strongly suggests that the sustained and transient channels might have differing integration times. The implication is, of course, that the difference in integration times reflects a difference in the visible persistence of these two channels. To test this hypothesis directly, some measure of visible persistence for stimuli of differing spatial frequency is needed. Meyer and Maguire (1977) attempted to measure visible persistence by having subjects judge the discontinuity of grating pattern. They alternated 50 msec grating presentations with a variable blank field. When the duration of the blank field was shorter than the visible persistence of the grating, the grating would appear to be continuously present. The duration of the blank field at the threshold of pattern continuity was used as a measure of persistence. Meyer and Maguire confirmed the results of the critical duration work of Breitmeyer and Ganz (1977) by demonstrating a shorter visible persistence for low frequency gratings than for high frequency gratings. Their estimates of persistence varied from 100 msec for 1 c/d to 500 msec for 15 c/d.

While Meyer and Maguire's (1977) results were in the predicted direction, there are several reasons why it is important to replicate their results using another paradigm. The method employed by Meyer and Maguire demands a psychophysical judgement of threshold. Such judgements depend on the subject's criterion for response and, the more difficult the task is, the more important the role played by criterion becomes in

the estimation of threshold. A judgement of pattern continuity is a difficult task, particularly when the stimulus is flickering. Earlier experiments by Keesey (1971) and Kulikowski and Tolhurst (1973) have demonstrated a cross-over of flicker and pattern thresholds as spatial frequency is increased. This means that subjects in Meyer and Maguire's experiment would be judging pattern continuity without flicker at low frequencies while they would have to contend with a flickering stimulus at higher frequencies. Thus, it is possible that Meyer and Maguire's results are confounded with a criterion shift caused by the presence of flicker in the high frequency stimuli.

The fact that Meyer and Maguire used a cycling presentation may also have influenced their results. In temporal integration studies, visible persistence is estimated by investigating the temporal overlap of the processing of two sequential events within the system. Experimenters who use cycling stimuli are assuming that there is no difference between processing in an activated system and processing in a previously inactive system. From recent neurophysiological studies (Singer & Phillips, 1973; Singer & Bedworth, 1973), it is clear that the on- and off-center cells of both the transient and sustained type are mutually inhibitory. This would mean that an activated system would have damping characteristics that would not be present in a previously inactive system. For this reason, the processing of a cycling stimulus may well differ from the processing of a two-pulse presentation.

In order to ensure that the relationship between persistence and spatial frequency demonstrated by Meyer and Maguire was not confounded by the factors mentioned above, it is desirable to replicate these findings using another method. This method should not employ a cycling

display, and, more importantly, should avoid possible biases in response-criterion inherent in estimation and judgement methods.

A paradigm that meets these requirements is one developed by Di Lollo and colleagues (Hogben & Di Lollo, 1974; Di Lollo, 1977; Di Lollo, in press (a)). This technique employs what is basically a two-pulse presentation and it does not require the subject to make a psychophysical judgement. Instead it requires that the subject use visible persistence to integrate visual information, allowing him to perform a location task. Di Lollo's technique employs a 5 X 5 matrix consisting of 25 elements. One element is always missing. The elements are displayed successively, either individually, or in groups. A variable temporal gap intervenes between the successive display of elements or portions of the matrix. The task of the subject is to locate the missing dot in the matrix. Since it is necessary that the whole display be visually available to the subject for him to do the task, some sort of visible persistence of the first elements presented is necessary to bridge the temporal gap between the first and last element. When the temporal gap is increased enough that the visible persistence of the first element fades before the last element is displayed, the subject's accuracy at locating the missing dot declines, and the task quickly becomes impossible. Hence, visible persistence can be estimated by varying the temporal gap until subjects just begin to make errors in the task.

Hogben and Di Lollo (1974) used two basic forms of this technique. In one, they presented the 24 elements in two groups of 12, separated by a temporal gap. This mode of presentation, termed "Flash", is most like Eriksen and Collins' (1967) original paradigm, as it is a two-pulse

presentation. Using the Flash mode, Hogben and Di Lollo found that subjects began to make errors when the temporal gap between the two flashes was more than 80 msec. The disadvantage of using this mode of presentation is that the distribution of errors cannot be used to determine the source of inaccuracy in the task. The second mode of presentation used by Hogben and Di Lollo allows a more detailed error analysis. In this mode, elements of the matrix are presented one by one, separated by a temporal gap. When the first element was presented more than 100 msec before the last element in the display, Hogben and Di Lollo found that subjects made errors in naming the location of the missing element. An analysis of these errors showed that subjects were most likely to confuse elements plotted early in the display sequence with the missing element. In addition to these findings, the study by these authors also demonstrated that, in this paradigm, it is the interval between the first and last element plotted that is important, irrespective of the regularity of temporal spacing. Di Lollo (in press(a)) extended the results of Hogben and Di Lollo (1974) showing that it was the interval between element onsets that determined accuracy at the task, rather than the duration of the gap. This means that visible persistence depends on the stimulus-onset-asynchrony (SOA).

The results of the experiments using this technique have been very consistent across subjects and stimulus conditions, even though a number of stimulus durations and element configurations have been used. The technique produces a robust effect and is ideal for testing the effect of varying spatial frequency on visible persistence. Both modes of presentation will be used in order to demonstrate the effect in a two-pulse presentation and still have access to a more detailed error analysis.

In this experiment, spatial frequency was manipulated using an ingenious technique developed by Von Grunau (1978). Instead of using displays that contained certain spatial frequencies, a basic display was developed containing a range of spatial frequencies. The high spatial frequencies of the display were then reduced by using lenses that defocused the image of the display on the subject's retina. The amount of high frequency content removed from the display was varied by changing the power of the defocusing lens.

In light of Meyer and Maguire's (1977) results and the conclusions drawn from previous studies (Breitmeyer & Ganz, 1977; Breitmeyer & Julez, 1975; Breitmeyer, 1975; Vassilev & Mitov, 1976), it is suggested that reducing high spatial frequencies by defocusing the display will reduce activity in the sustained channels. As sustained channels have a longer persistence, this will result in a shorter visible persistence for each element of the display. Thus, at any given temporal gap, the apparent overlap between successively presented elements or groups of elements will be less when the matrix is defocused. In terms of the location task, this means that subjects will begin to make errors at shorter intervals between the onsets of the first and last elements when the matrix is defocused.

Method

Apparatus and Stimulus Display

General. The apparatus and technique used in this experiment are similar to those employed by Di Lollo and colleagues in a number of recent studies (Hogben & Di Lollo, 1974; Di Lollo, 1977; Di Lollo, in press (a)). Elements of a matrix of five rows by five columns were presented in a temporally discontinuous manner. One element of the 25 was chosen to be left out. The subject's task was to name the location of the missing element.

The display, consisting of 24 of the 25 elements defining the five by five square matrix, was plotted on a Hewlett-Packard 1333A point-plotter equipped with P15 fast phosphor. A PDP-8/L computer controlled the generation of the display, as well as all timing and scoring functions. Each element in the matrix was plotted only once, and the plotting order was randomized. Plotting time per element was 0.2 msec.

Size of Display. Each element of the matrix consisted of a square made up of nine single points plotted 0.25° of visual angle apart. Individual squares subtended 0.5° visual angle and were spaced 1° apart. The matrix as a whole subtended 6.5° visual angle. One fixation point was plotted at each corner of the matrix, about 12° from the center of the display screen.

Intensity of Display. Absolute photometric measurements for the display cannot be given, as the duration of the display is very brief and it cannot be assumed that there is a linear relationship between intensity and the voltage applied to the z-axis of the point-plotter via a digital-to-analog converter. However, using calibration procedures described by Di Lollo (in press (b)), it is possible to maintain a fixed

intensity level across all sessions. The specific calibration procedure used in this experiment employed a test patch consisting of 400 points plotted in a 20 by 20 square which covered an area of 7.0 by 7.0 mm in the center of the display surface. This test patch was continuously plotted at a rate of 44 points/msec. The gain on the point-plotter was adjusted so that this standard patch (plotted at a z-value of 1000_8) had an illuminance of 0.04 lux as read on a Tectronix J16 Photometer. the z-value used to plot the matrix itself was set at 1300_8 for the main part of the experiment. When the matrix was displayed at this intensity with a plotting interval of 20 msec, the display was approximately 3.4 log above threshold. With the gain on the point-plotter fixed by the procedure mentioned above, the illuminance reading for the continuous standard patch at a z-value of 1300_8 was 0.206 lux. As mentioned previously, these photometric measurements are not valid across a range of point-plotters or oscilloscopes, or in different laboratories. They do, however, ensure a fixed intensity across sessions in this laboratory, given a fixed stimulus configuration and a constant plotting rate.

Mode of Display Presentations. Two modes of presenting the matrix were used. In the Ripple mode, the 24 elements were displayed singly, in random order, at regular inter-element-intervals (IEI). The IEI was systematically varied so that the total plotting interval of the matrix, from onset of the first element to the offset of the last element, varied between 20 and 160 msec in 8 steps of 20 msec each. In the Flash mode, the matrix was displayed in two successive flashes of 12 simultaneous elements, randomly chosen on each trial. Each flash took 2.5 msec to plot. The two flashes were separated by an inter-flash-interval (IFI), which was systematically varied so that the total plotting

interval of the display from onset of the first flash to offset of the second flash varied between 20 and 160 msec in 20 msec steps. A visual representation of the two modes of matrix presentation is given in Figure 1.

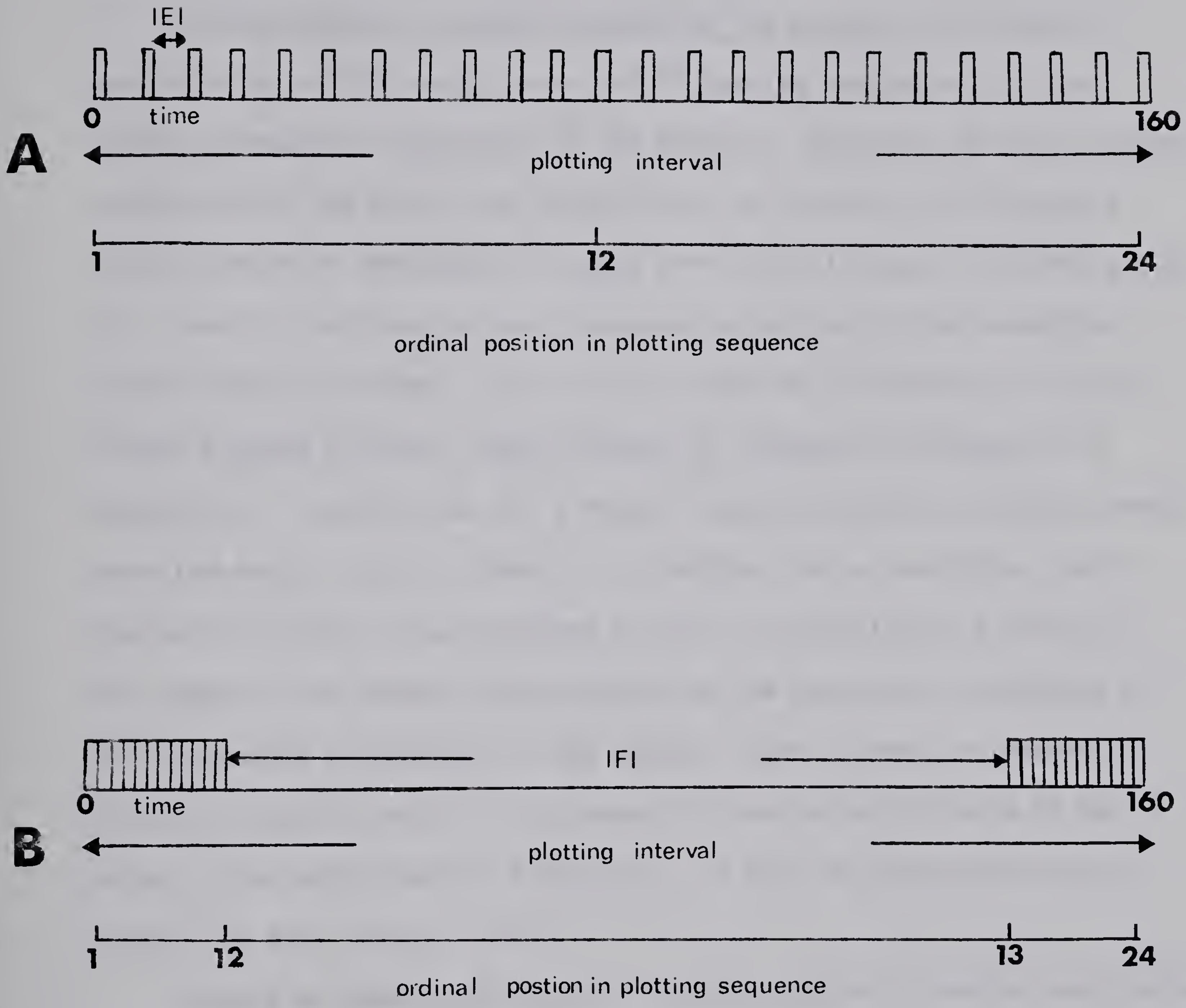
Procedure and Subjects

General. Subjects were seated in a darkened chamber equipped with an intercom system and display button. They viewed the display through a standard Tektronix 016-0154-00 viewing hood attached to the point-plotter. In all conditions, the subject's task was to name the location of the missing element by naming the row and column number. A trial proceeded as follows. First, four fixation dots were presented to the subject. When he was ready to proceed with the trial, the subject displayed the matrix by pressing the display button. Following the display, the subject reported his response to the experimenter via the intercom system. The experimenter entered the response into the computer via the teletype and a complete set of trial information was printed out. Following this, the fixation dots reappeared, indicating the beginning of the next trial.

The print-out for each trial contained information on the plotting interval used in the trial, the correct location of the missing element, and the subject's response. In the case of an incorrect response, the computer also printed out the ordinal position of the misidentified element in the plotting sequence.

In the main experiment, there were two modes of presentation and four defocusing conditions. These factors were varied across sessions, with five sessions at each level of defocusing in both the Ripple and Flash mode. Each session contained 80 trials; 10 trials at each

Figure 1. A diagramatic representation of the modes of presentation. Elements are shown plotted over time with the ordinal plotting sequence given below each time axis. (A) Ripple mode; IEI represents temporal gap between elements. (B) Flash mode; IFI represents temporal gap between flashes. Figure is not drawn to scale.


IEI
0
time
160
A
plotting interval
1
12
24
ordinal position in plotting sequence
IFI
0
time
160
B
plotting interval
1
12
13
24
ordinal postion in plotting sequence

of the 8 plotting intervals. Trials occurred in random order within each session. In summary, the experiment consisted of a four by two by eight factorial design. For every subject, there was a total of 50 trials for each plotting interval at every level of defocusing for both modes of presentation.

Varying Spatial Frequency Content of the Display. The major manipulation in this study consisted of varying the amount of high spatial frequency information in the display. Reduction of high frequency components of the matrix was accomplished by the use of Von Grunau's (1978) method of defocusing an image with optical lenses. In this study, four levels of defocusing were produced by the use of four negative diopter (D) lens values: 0D, -2D, -4D, and -6D. Subjects wore these lenses clipped to their normal glasses or inserted in optometrist's spectacles. Condition 0D was a normal viewing condition; subjects merely wore the empty clips or frames. In the other three conditions, each increasing diopter value produced increased defocusing or blurring of the image at the retina, corresponding to the decreasing prominence of high frequency componenets in the image. Table 1 shows the amount of blurring caused by each of the lenses in terms of an estimate of the highest resolvable spatial frequencies, as well as the magnification factor for each diopter value.

It must be remembered that the display contains a complex combination of spatial frequencies, making it difficult to specify the actual power spectrum. In addition, the characteristic transfer functions of the lenses may, in themselves, be complex. Thus, it is impossible to specify the exact effect of the lenses on the display. However, an estimate of the defocusing effect can be provided if calculations are based on the

Table 1

Highest Resolvable Spatial Frequency and Magnification Factors for each Diopter Value*

Diopter Value	Highest Resolvable Spatial Frequency**	Magnification Factor
0D	60 c/d	1
-2D	3.49 c/d	.99
-4D	1.71 c/d	.98
-6D	1.41 c/d	.97

*Formulas used in calculations are presented in Appendix 1.

**Raleigh's criterion of resolvable distance equals radius of blur circle (see Longhurst, 1957) was used to derive these values.

subject's ability to resolve the high spatial frequencies within any display.

Subjects. Four subjects, two male and two female, participated in this experiment. The ages of the subjects ranged from 28 to 48, and all subjects had normal, or corrected-to-normal vision. Two of the subjects (VDL, EW) were practiced psychophysical observers, while the other two were naive to the procedure (CW, MH).

Varying Intensity of the Display. Following the main experiment, a series of control sessions were run in Condition OD at two lower levels of stimulus intensity to ensure that variations in luminance caused by defocusing were not confounded with the manipulation of spatial frequency. The same experimental procedure was followed. The z-values used to plot the matrix for these conditons were 700_8 and 600_8. These values correspond to 0.014 lux and 0.003 lux respectively, as measured by the calibration procedure mentioned above. Again, it must be noted that these values only indicated the ordinal position of the intensity settings, and cannot be used to derive relative photometric values. Psychophysical measures taken on the matrix displayed at the shortest plotting interval using these values showed that they were 2.0 and 1.4 log above threshold, respectively.

The two levels of display intensity and the two modes of presentation were varied across sessions. Plotting interval was varied within sessions. As with the main experiment, there were five sessions at each intensity level for both modes, and each session contained 80 trials; 10 at each plotting interval. The resulting factorial design was a two by two by eight design with 50 trials in each cell.

Two of the four subjects from the main experiment (VDL, EW) participated in these control sessions.

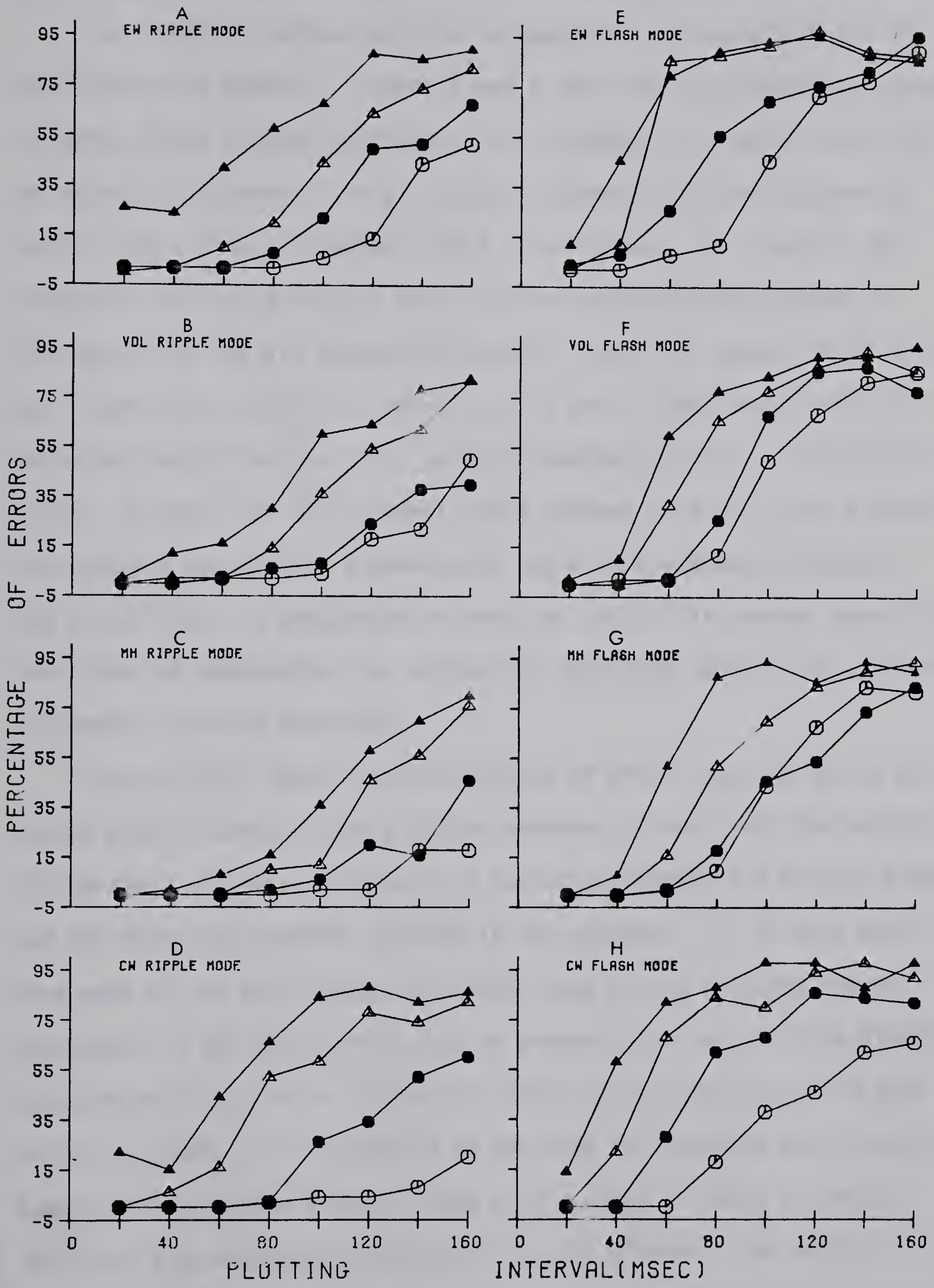
Results

Varying Spatial Frequency Content

The results for all subjects are presented in Figure 2 (A-H) in terms of the percentage of errors made at the various plotting intervals. The four curves in each graph represent the data for the four levels of defocusing for each subject. It has been previously noted that the plotting interval was measured from the onset of the first element plotted to the offset of the last element in both modes of presentation. Since the actual plotting time of the matrix elements was constant at 5 msec, this means that the plotting interval varied directly with SOA. As a result, increasing the plotting interval by 40 msec would also increase the SOA by 40 msec. While the results will be described and discussed in terms of plotting interval, it is clear that it will be possible to generalize the conclusions to situations in which SOA has been manipulated.

All the curves in Figure 2 show that subjects made more errors as the plotting interval was lengthened. At short plotting intervals, the task was performed very well; but, as the interval was increased, it became more difficult for the subjects to identify the missing element correctly. When the four curves in each graph are compared, it can be seen that ability to name the missing element was affected by the level of defocusing in a systematic manner. As the level of defocusing was increased, subjects began to make errors at shorter plotting intervals. This effect is seen in both modes of presentation. It should be noted that the shapes of the curves for the two modes also differ. A comparison of the Flash mode (2E, F, G, H) with the Ripple mode (2A, B, C, D) curves reveals that subjects began to make errors at shorter

Figure 2. Percentage errors in identifying the location of the missing element for levels of defocusing. Plotting interval of the matrix is shown on the abscissa; percentage of errors on the ordinate. Four defocusing conditions are represented on each graph: (○) - 0D, (●) - -2D, (△) - -4D, (▲) - -6D. Two graphs are shown for each subject. (A-D) Ripple mode. (E-H) Flash mode.


A
EW RIPPLE MODE
B
VDL RIPPLE MODE
C
MH RIPPLE MODE
D
CW RIPPLE MODE
E
EW FLASH MODE
F
VDL FLASH MODE
G
MH FLASH MODE
H
CW FLASH MODE
95
75
55
35
15
-5
0
40
80
120
160
PERCENTAGE OF ERRORS
PLOTTING INTERVAL(MSEC)

plotting intervals in the Flash mode, and the percentage errors increased more rapidly in this mode than it did in the Ripple mode.

The effect of defocusing is also apparent in the analysis of the distribution of errors. Figures 3 and 4 show the distribution of errors in terms of the ordinal position of the elements incorrectly identified as the missing element. As all subjects showed a similar pattern of results, data from one subject (VDL) is presented. In Figure 3, the proportion of errors made in the first and second flash is shown in histogram form for all plotting intervals. The four graphs (Fig. 3A-D) each represent a level of defocusing. It can be seen that almost all incorrect identifications were made for elements plotted in the first flash. In fact, for this subject, 98.6 percent of errors were a result of confusing the missing element with one of the elements plotted in the first flash. A comparison of the four sets of histograms demonstrates the effect of defocusing. As defocusing increased, errors are apparent at shorter plotting intervals.

Figure 4(A-D) shows the distribution of errors made by VDL in the Ripple mode in terms of the plotting sequence. Here again the majority (72 percent) of errors are due to a confusion between the missing element and the first six elements plotted in the sequence. It is also clear from each of the four series of graphs, that as the plotting interval increased, it was more likely that an element from later in the plotting sequence would be chosen. Using the time scale at the bottom of each series of graphs, it is possible to see what is happening more clearly. Subjects always chose elements that were plotted at least a certain length of time before the offset of the last element. For example, in Condition OD, most incorrect identifications occurred for elements

Figure 3. Temporal distribution of errors in the Flash mode for levels of defocusing. Plotting interval of the matrix is shown on the abscissa. Unshaded bars represent the proportion of trials on which an element from the first flash was chosen as the missing element. Shaded bars represent the proportion of trials on which an element from the second flash was chosen. (A) Condition 0D. (B) Condition -2D. (C) Condition -4D. (D) Condition -6D. Data are presented for one subject (VDL).

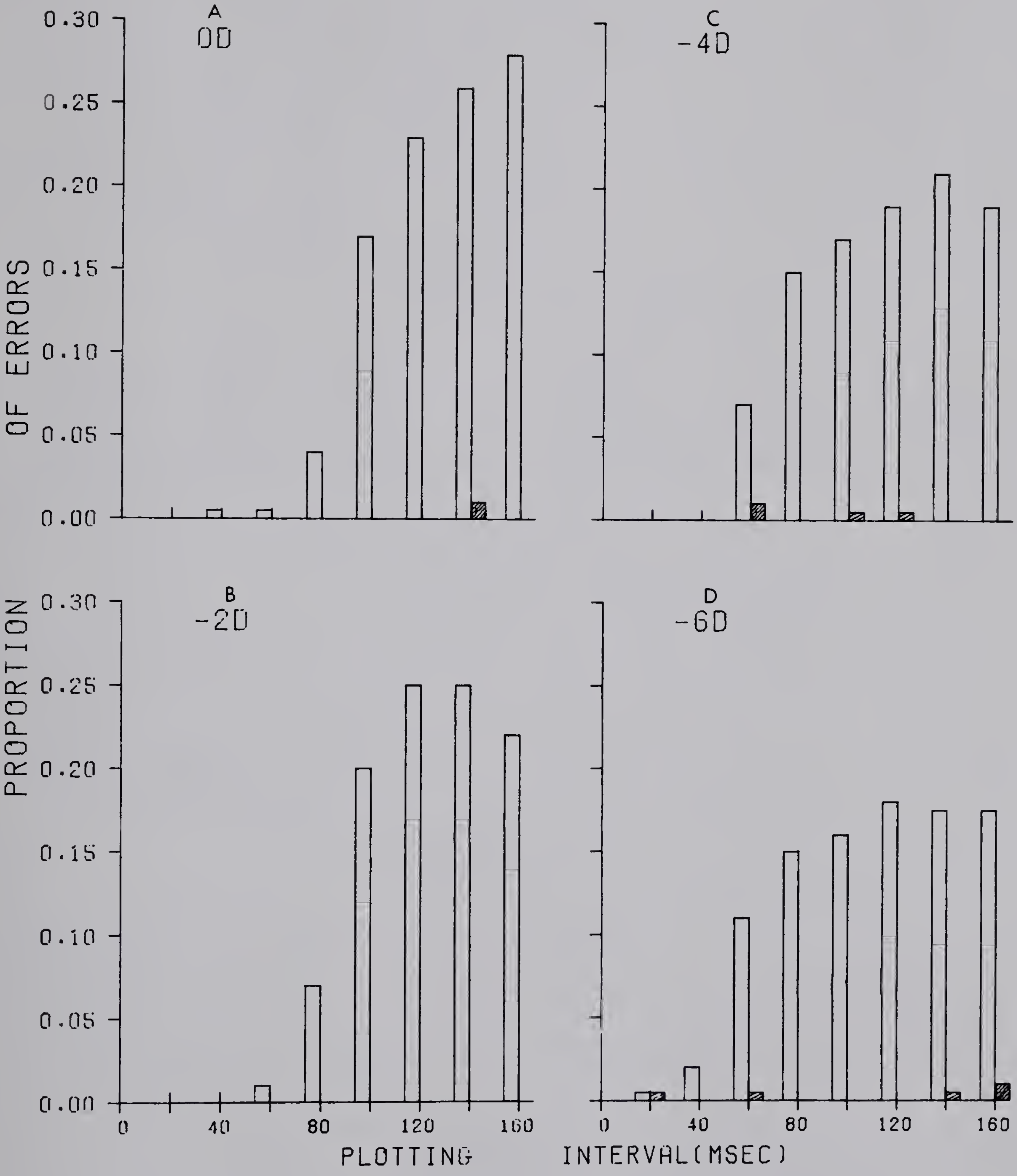
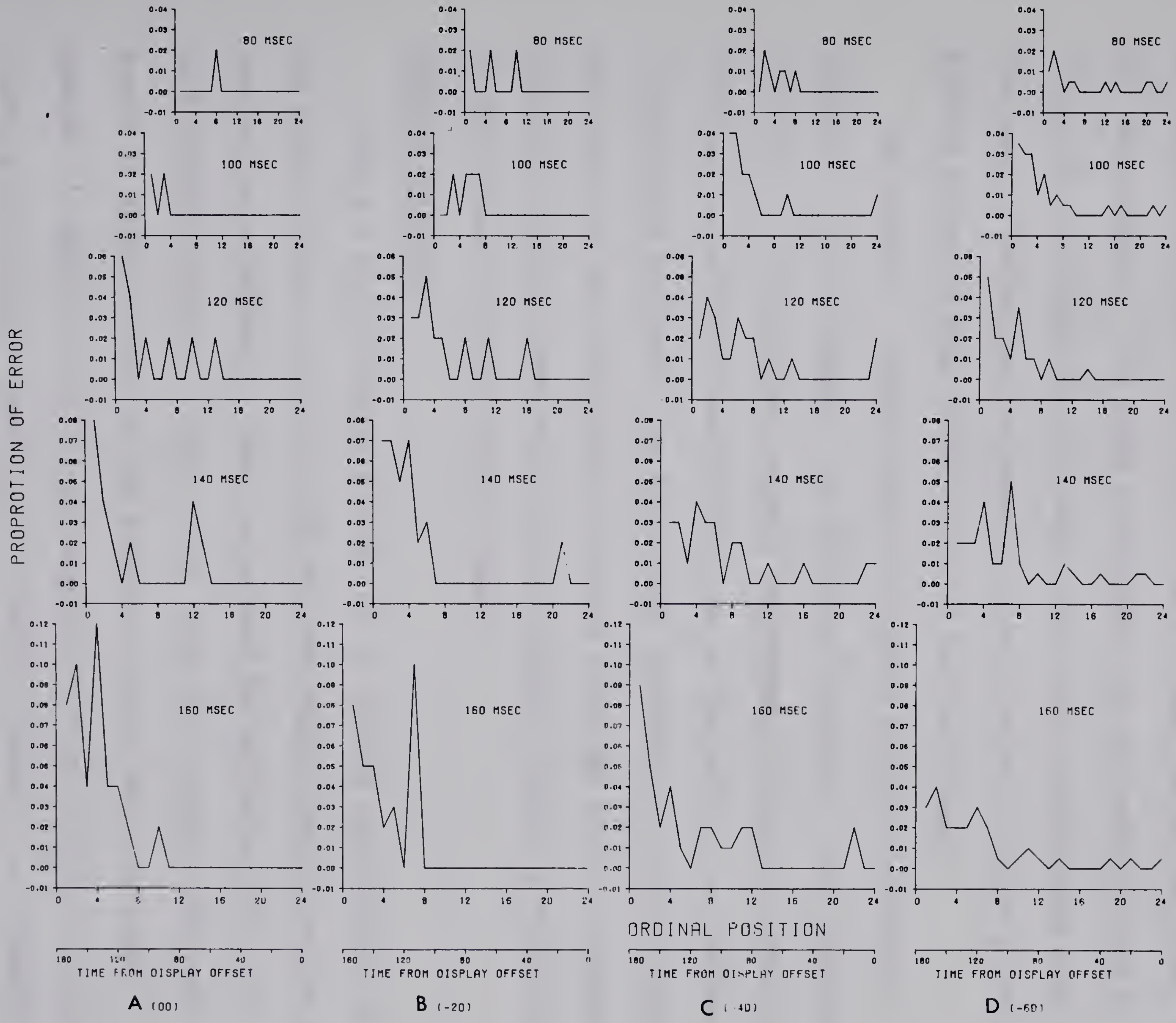

A
0D
B
-2D
C
-4D
D
-6D
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
40
80
120
160
PROPORTION OF ERRORS
PLOTTING INTERVAL(MSEC)

Figure 4. Temporal distribution of errors in the Ripple mode for levels of defocusing. Within each graph, the abscissa indicates the ordinal position of each element within the plotting sequence, irrespective of spatial location. The ordinate shows the proportion of trials on which an element plotted at the indicated ordinal position was incorrectly identified as missing. Each set of five graphs represents the results for one defocusing condition: (A) 0D; (B) -2D; (C) -4D; (D) -6D. Within a series, each graph represents the results from one plotting interval. Plotting interval is indicated in the upper right-hand corner of each graph. Data are presented for one subject (VDL).


PROPROTION OF ERROR
80 MSEC
100 MSEC
120 MSEC
140 MSEC
160 MSEC
ORDINAL POSITION
0
4
8
12
16
20
24
180
120
80
40
0
TIME FROM DISPLAY OFFSET
A (00)
B (-20)
C (-40)
D (-60)

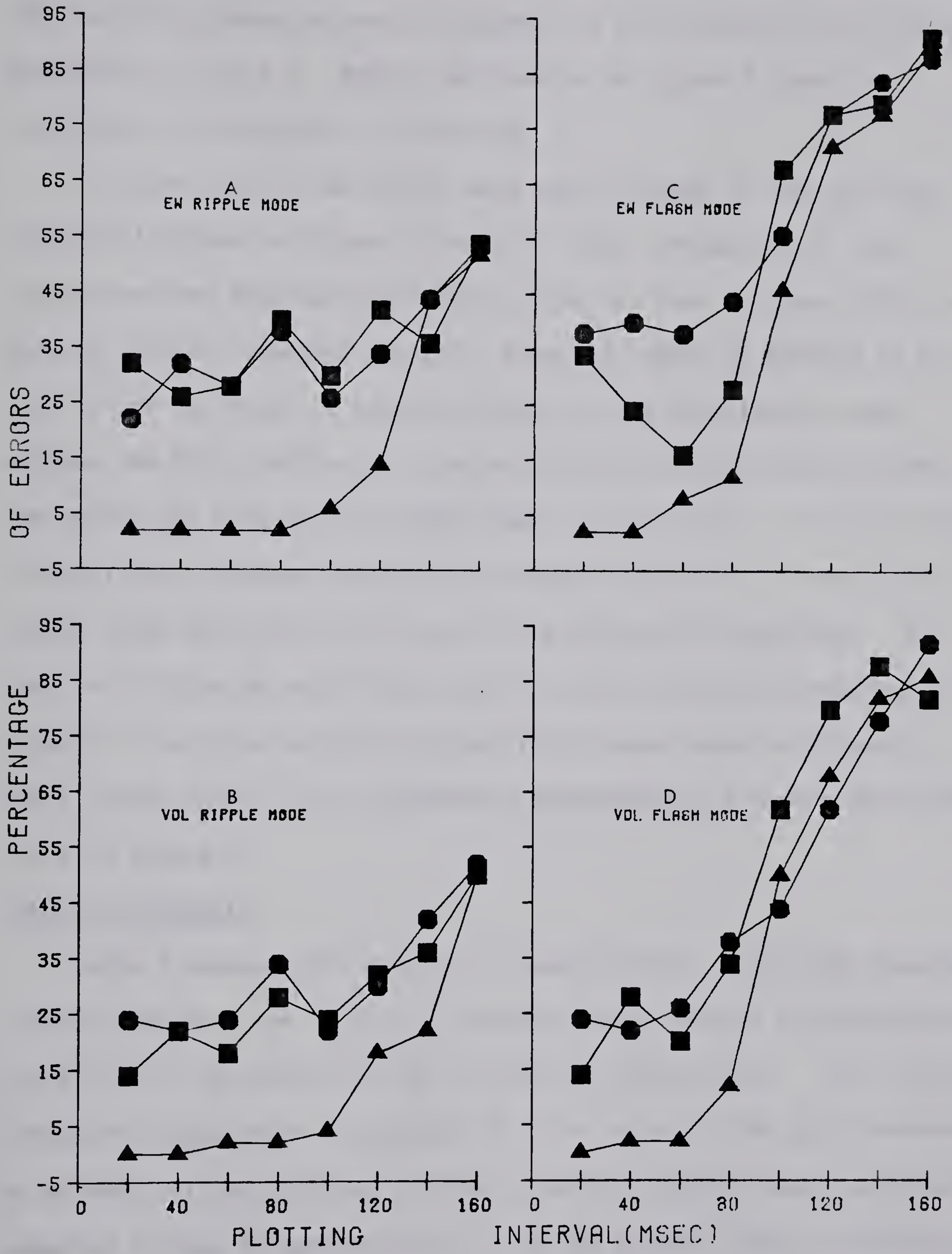
plotted at least 100 msec before offset of the last element. This corresponds with the fact that subjects began to make errors when the plotting interval exceeded 100 msec (see Fig. 2). However, when the matrix is defocused with a -4D lens, the majority of errors are made by identifying elements plotted at least 80 msec before the offset of the last element. This again corresponds with the results shown in Figure 2B, Condition -4D. The error data clearly demonstrate that, as the level of defocusing increased, subjects tended to choose elements plotted closer in time to the offset of the last element.

The results of varying spatial frequency can be summarized as follows. While performance was initially faultless at short plotting intervals, as the plotting interval lengthened, it became increasingly difficult to correctly identify the hole in the matrix. As the level of defocusing increased, the task became difficult at shorter intervals. An analysis of the distribution of errors along the plotting sequence shows that subjects were most likely to confuse elements plotted early in the sequence with the missing element.

Varying Intensity

Figure 5 (A-C) presents the results of varying the intensity of the matrix display in Condition 0D for both subjects who served in this part of the experiment. These graphs show the percentage errors at each plotting interval. Again, it is clear that subjects made more errors in identification as the plotting interval was lengthened. However, it should be noted that subjects had more difficulty in correctly locating the missing element at all plotting intervals, as intensity was reduced. This differs from the results presented in the last section, where the task was always performed accurately at the shortest plotting

Figure 5. Percentage errors in identifying the location of the missing element for levels of intensity. Plotting interval of the matrix is shown on the abscissa, percentage errors on the ordinate. Three intensity levels, indicated here by the z-values used in plotting the matrix, are represented on each graph: (▲) -1300, (■) -700, (●) -600. Two graphs are shown for each subject. (A,B) Ripple mode. (C,D) Flash mode.


A
EW RIPPLE MODE
B
VOL RIPPLE MODE
C
EW FLASH MODE
D
VOL. FLASH MODE
PERCENTAGE OF ERRORS
PLOTTING INTERVAL(MSEC)
95
85
75
65
55
45
35
25
15
5
-5
0
40
80
120
160

intervals. A comparison for Figures 2 and 5 reveals that the systematic differences in the family of curves for each subject obtained by varying the level of defocusing seen in Figure 2 is not apparent in the curves presented in Figure 5. Hence, the results in Figure 2 cannot be attributed to variations in luminance.

A closer look at how errors were made in terms of the plotting sequence is given in Figures 6 and 7 for VDL. Inspection of these graphs confirms that varying intensity did not have the same effect as varying spatial frequency content. Figure 6, which is plotted in the same manner as Figure 3, shows that errors were distributed evenly between the first and second flash at shorter plotting intervals when the matrix was displayed at lower levels of intensity. As the plotting interval was increased, subjects continued to make more errors in the second flash than they did in any of the defocusing conditions. The same pattern can be seen in the data for the Ripple mode presented in Figure 7. Here the data are plotted in the same manner as Figure 4. These graphs reveal a less systematic distribution of errors than that found in Figure 4.

Summary of Results

Table 2 presents the results in summary form. These data have been interpolated from the family of curves for each subject to demonstrate the effect of defocusing and of the mode of presentation. The interpolation procedure is described in Appendix 2. The values in the table represent an estimate of the plotting interval at which subjects would have been expected to make 50 percent errors. The 50 percent level was chosen as the criterion for interpolation, as it intersects the steepest portion

Figure 6. Temporal distribution of errors in the Flash mode for levels of intensity. Plotting interval of the matrix is shown on the abscissa. Unshaded bars represent the proportion of trials on which an element from the first flash was chosen as the missing element. Shaded bars represent the proportion of trials on which an element from the second flash was chosen. Each graph shows the results for one intensity condition, given here in terms of the z-value used to plot the matrix: (A) 1300, (B) 700, (C) 600. Data are presented for one subject (VDL).

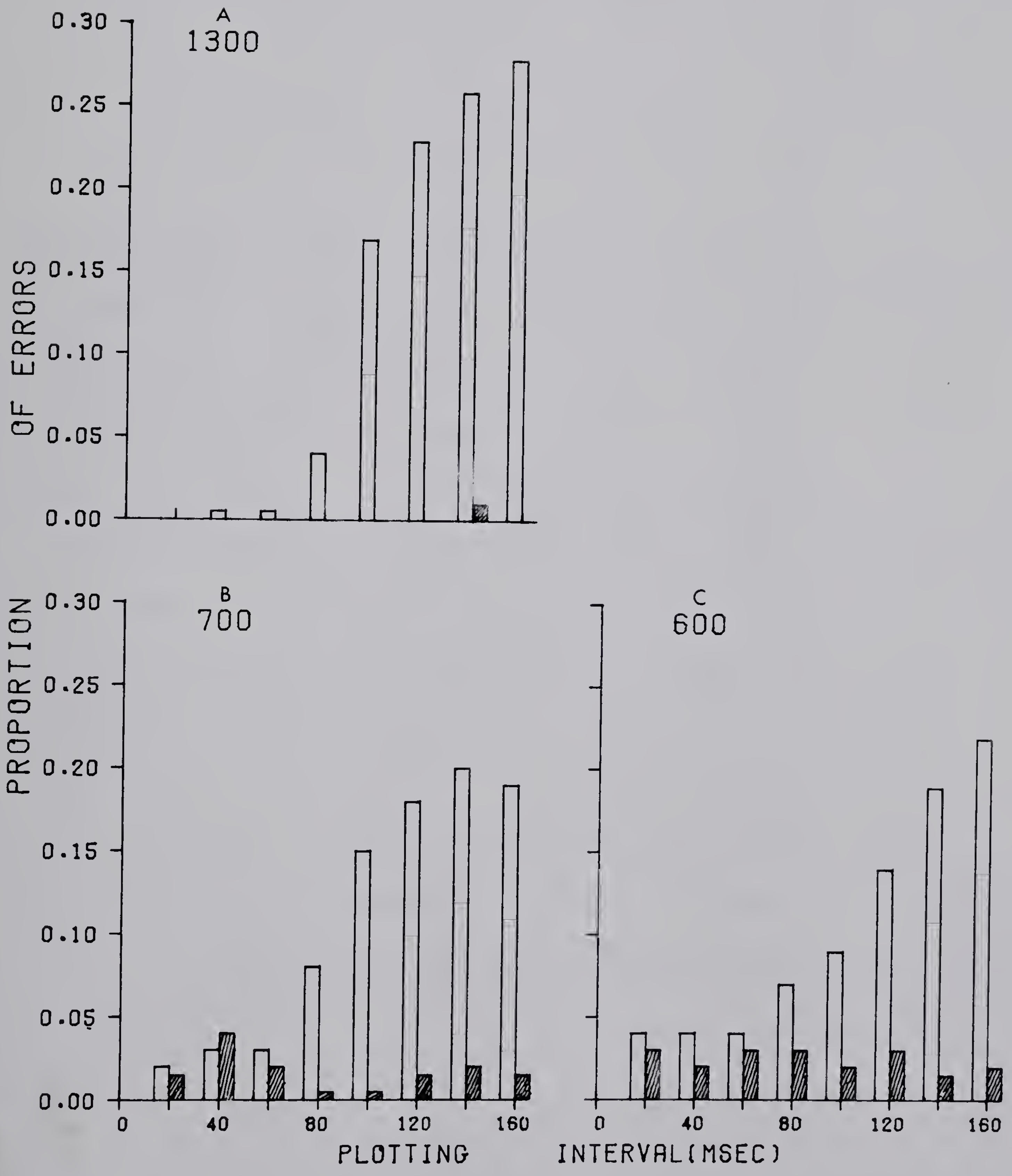
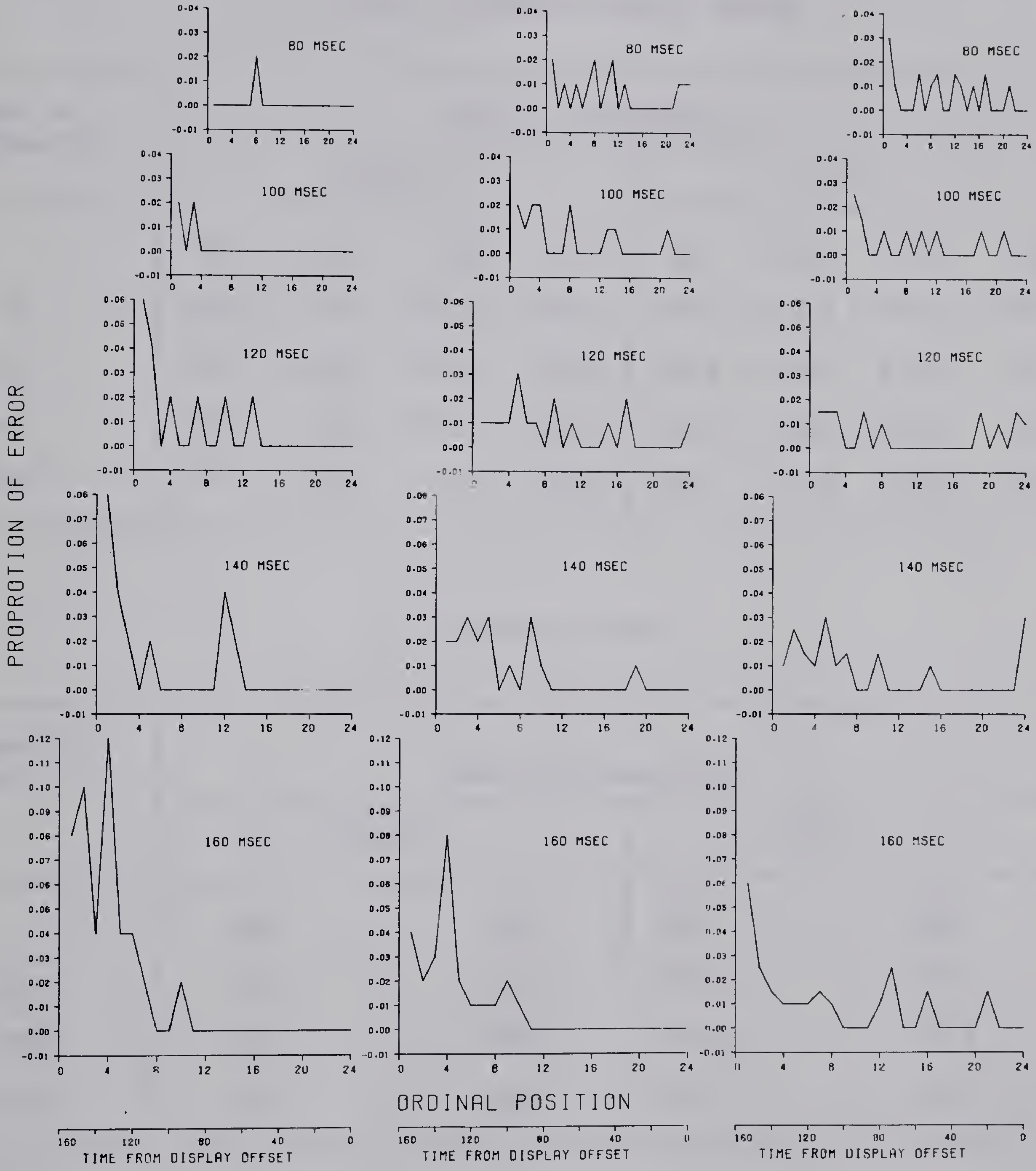

A
1300
B
700
C
600
PROPORTION OF ERRORS
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
40
80
120
160
PLOTTING INTERVAL(MSEC)

Figure 7. Temporal distribution of errors in the Ripple mode for levels of intensity. Within each graph, the abscissa indicates the ordinal position of each element within the plotting sequence, irrespective of spatial location. The ordinate shows the proportion of trials on which an element plotted at the indicated ordinal position was incorrectly identified as missing. Each set of five graphs represents the results for one level of intensity given here by the z-values used in plotting the matrix: (A) 1300, (B) 700, (C) 600. Within a series, each graph represents the results from one plotting interval. Plotting interval is indicated in the upper right-hand corner of each graph. Data are presented for one subject (VDL).



A (1300) B (700) C (600)

Table 2

Plotting Interval Values for 50 Percent Error (Msec)

A. Spatial Frequency Content Varied

Level of Defocusing	Mode of Presentation							
	Ripple				Flash			
	EW	VDL	MH	CW	EW	VDL	MH	CW
0D	160.0	>160.0	>160.0	>160.0	105.0	105.0	107.0	123.5
-2D	151.0	>160.0	>160.0	141.0	78.0	92.0	111.0	71.5
-4D	107.5	118.0	129.0	84.0	51.0	72.5	82.0	53.5
-6D	71.0	97.0	114.0	64.0	42.5	58.5	60.0	38.0

B. Intensity Varied

Intensity Level	Mode of Presentation			
	Ripple		Flash	
	EW	VDL	EW	VDL
1300	160.0	>160.0	105.0	105.0
700	153.5	>160.0	92.0	91.5
600	152.0	156.0	87.0	104.0

of most curves, providing the most reliable estimates of the plotting interval for the purposes of comparison. It should be noted that these values are not estimates of persistence, but serve to summarize the systematic differences in the family of curves for each subject. As such, they reflect the differences in persistence caused by defocusing.

Table 2A demonstrates that the plotting interval for 50 percent errors decreased with increasing levels of defocusing. It also shows the difference between the two modes. Both these differences proved to be significant ($p<.01$) when an analysis of variance was done on the values. A summary table of this analysis is presented in Appendix 3.

The results of varying intensity are presented in Table 2B. These values do not show any change in plotting interval for variations in intensity. They do, however, demonstrate the difference between the two modes.

The data in Table 2A clearly reflect the systematic changes in the family of curves for each subject when the level of defocusing was manipulated. Reducing spatial frequency content by defocusing affected the subjects' ability to integrate the display information, so that errors began to occur at shorter plotting intervals. On the other hand, the data from Table 2B clearly confirm the suggestion that decreasing intensity did not affect performance in the same manner as defocusing. Reducing intensity reduced the subjects' ability to perform the task at all plotting intervals. It did not change the relationship between change in accuracy and plotting interval.

Discussion

The results of this study strongly suggest that duration of visible persistence decreases as the prominence of high spatial frequency components is reduced by defocusing. The family of curves produced by each of the four subjects showed that defocusing, while not increasing task difficulty at all plotting intervals, did produce at least a three-fold decrement in the duration of plotting interval where errors began to increase.

Effect of Plotting Interval

When the matrix was fully in focus (0D condition), the results for every subject essentially replicated the findings of other studies using this technique (Hogben & Di Lollo, 1974; Di Lollo, 1977; Di Lollo, in press (a)). Subjects' ability to locate the missing element decreased as the plotting interval lengthened. The distribution of error data suggests that subjects confused the missing element with elements presented early in the plotting sequence. It would seem then, that, at the longer plotting intervals, a proportion of the first elements plotted was not available to the subject by the time the last element appeared. Subjects' casual observations confirmed this. At the shortest plotting intervals, they reported that all elements appeared simultaneously, and the missing element was easy to locate. However, in the Ripple mode, when the plotting intervals reached 100 msec, subjects reported that they had several holes to choose from. In the Flash mode, subjects began to report seeing two separate groups of 12 elements at plotting intervals of 80 msec (see Figure 2).

It might be suggested that the disappearance of the early elements can be accounted for by metacontrast masking of these elements by later

ones. Certainly, elements plotted early in the sequence (or in the first flash) have a higher probability of being masked than do elements that are plotted later. However, an experiment reported by Hogben and Di Lollo (1974) indicates that metacontrast is not an important factor in this paradigm. These authors reported the results of an experiment in which the matrix was plotted in four flashes of six elements each. If masking were to account for the errors made, it would be expected that the percentage of errors would be greatest when the flashes were separated by 60 to 100 msec, as this is the SOA at which the masking of one element by another would be most effective. There was no evidence of such a maximal masking effect at 60 to 100 msec SOA between any of the four flashes. While masking may have had a small effect on some trials in either mode, it is obviously not the major cause of misidentification.

A more plausible explanation of the results is that, when the plotting interval was long enough, the visible persistence of the first elements in the sequence faded before the last element could be plotted. Hence, all matrix elements would not be simultaneously available to the subject at the longer plotting intervals. At these intervals, locations where the first elements in the plotting sequence were displayed would appear as holes by the time the final element in the matrix had been plotted. Thus, when a subject viewed the matrix displayed at a sufficiently long interval, he actually had several holes to choose from. In making his response, he was as likely to name the location of a faded element as he was to name the location of the missing element.

In the Ripple mode, this means that when the temporal gap between the plotting of the first and the last element exceeded the visible persistence of the first element, the subjects had two holes to choose from.

When they made errors, it was probably due to misidentifying the faded element as the missing element. As the plotting interval lengthened, more of the early elements would be unavailable; their persistence having faded before the last element could be plotted. Hence, subjects would have had to choose from a larger number of holes as the plotting interval was increased. The error distributions shown in Figure 4 reflect this procedure. As the plotting interval increased, more of the locations of early elements were incorrectly named as the location of the missing element.

In the Flash mode, the first 12 elements were plotted within 2.5 msec. Thus, the persistence of all elements began to fade at approximately the same time. This means that when the interval between the first and second flash exceeded the persistence of the elements presented in the first flash, the subject had 12 holes to choose from in addition to the hole caused by the missing element. Under these conditions, subjects were most likely to name one of these twelve locations as the location of the missing element when they made an incorrect response (see Figure 3).

The difference in the shape of the curves for the two modes of presentation may relate to the difference in the number of elements whose persistence faded before the matrix was completely plotted. As mentioned previously, in the Ripple mode, subjects had an increasing number of holes to choose from as the plotting interval lengthened. This would mean that the probability of a subject guessing the correct location of the missing element from the apparent holes in the matrix decreased from 50 percent as the plotting interval increased. On the other hand, persistence for all elements plotted in the first flash of

the matrix presented in the Flash mode faded at the same time. In the Flash mode, then, subjects were always guessing from 13 holes as long as the plotting interval exceeded the persistence of the first flash. This difference in probability may account for the difference in slopes for the two curves. The more gradual slope of the Ripple mode curves may be attributed to the higher probability of guessing the location of the missing element correctly at the shorter plotting intervals. However, there is still a difference between the modes of 20 msec on average for the interval at which subjects began to show a decrease in accuracy. While this difference in part also may be due to the difference in probability of a correct guess, there is another possible explanation. It could be the case that the rapid onset of 12 dots together may have evoked a larger amplitude transient response than would have been produced by a Ripple presentation. If persistence depends on the relative activity in the two types of channels, this extra weighting towards the transient activity may have caused an actual difference in the average persistence of the display. The importance of the relative weighting of transient and sustained activity will be discussed more fully in a later section.

Effect of Defocusing

The effect of defocusing is quite clear. It has been shown that, as the level of defocusing increases, the high frequency content of the retinal image is reduced. The family of curves presented for each subject in Figure 2 demonstrates that, as high frequencies were reduced, the maximum plotting interval that allows full integration of all elements in the display was also reduced. In other words, the plotting interval at which subjects began to make errors was shorter for each level of

defocusing. Altogether, this amounts to a three-fold decrease in the persistence of the display over the four levels of defocusing used. In Condition OD, errors began to increase at 100 msec in the Ripple mode. In Condition -6D, the increase in errors occurred at 40 msec for the same mode of presentation. The error analysis and the fact that the subjects were able to perform the task easily at the shortest plotting interval indicate that the defocusing is in fact decreasing the persistence rather than increasing the difficulty of the location task per se. The data for two subjects, EW and CW, show a partial deviation from this generalization. For these subjects, the curves for the -6D condition show a slight elevation in error rate for the shortest plotting intervals. This would indicate that, for these subjects, the general task was actually more difficult in the -6D condition. Two possible reasons are offered for these data. Increasing the blurring of the matrix in an extreme fashion is bound to eventually make the location task impossible, by turning the matrix into a sheet of light. It may be that the -6D condition produced a manipulation of the basic task that was too extreme for these two subjects. Both EW and CW had normal or near-normal vision, and were therefore less accustomed to interpreting blurred information than were the other two subjects whose vision (in the uncorrected state) was much poorer. This contention receives support from EW and CW's observations that the matrix appeared so blurred in the -6D condition that sometimes there did not appear to be any holes in the matrix when all elements appeared to be simultaneously present. The other suggestion is more speculative. Both subjects who showed this elevation in errors were female. It has been shown that women often perform more poorly than men on difficult spatial tasks.

Since this task is definitely one which taps spatial abilities, it may be the case that the -6D condition overtaxed the abilities of the female subjects, but did not exceed the abilities of the male subjects. Of course, many more subjects would have to be run to confirm either of these possibilities. At any rate, the results of these two subjects in the -6D condition serve to point out what the results look like when errors caused by a decrease in persistence are contaminated by errors due to an increase in the difficulty of the task. They also demonstrate that the matrix has been defocused as far as possible in the -6D condition while still allowing the task to be performed by most subjects.

Some Physiological Considerations

From the studies cited earlier in this paper, it is clear that sustained channels respond to high spatial frequencies and transient channels respond to low spatial frequencies. In addition, the psychophysical results indicate that sustained channels should have longer persistences than transient channels. Using this information, the simplest explanation of the results presented here would be that reducing the high spatial frequency content reduced the amplitude of the response in the sustained channels. Reducing the sustained channel's response reduced the contribution of these channels to the visible persistence of the display. This explanation may help to account for the difference between the Flash and Ripple curves. It could be that the manner of presentation used in the Flash mode weighted the transient information more heavily to begin with, resulting in a lower average persistence in all defocusing conditions.

However, if there were simply two characteristic persistences, one for sustained channels and the other for transient channels, one might

expect that the data would show one abrupt change in persistence. For instance, the results for Conditions 0D and -2D might be expected to show errors increasing at a plotting interval of 100 msec, while Conditions -4D and -6D might show an increase in errors at a plotting interval of 40 msec. But the family of curves for each subject in Figure 2 shows a gradual change in the value of plotting interval at which the first increase in errors occurred. It is possible that this is due to the specific method employed in this study to reduce spatial frequency content. However, the data from other studies show the same gradual shift in persistence (e.g. Meyer & Maguire, 1977), or processing time (e.g. Breitmeyer, 1975) as spatial frequency is decreased. Studies showing an abrupt change in persistence over spatial frequency are notably absent. It might be possible to explain this gradual change in the duration of persistence in terms of the probability of a sustained response being below threshold on any given trial. For example, if a display contained spatial frequencies which had a 50 percent chance of activating the sustained channels, then on 50 percent of the trials, the persistence of the display would reflect sustained activity, while in the remaining trials, the persistence of the display would only reflect transient activity. In the data, this kind of procedure would show up as variance around the mean for each data point in the curves in Figure 2. However, there was surprisingly little variance in the five sets of ten values making up each data point. In other words, the gradual shift would be apparent even if the data for each session had been plotted individually. This is inconsistent with a probability hypothesis and leads to the conclusion that an alternative explanation should be considered.

Another aspect of the data should be considered in this regard. An explanation of changes in the duration of visible persistence based on the existence of two types of channel activity would seem to imply that persistence can only be reduced so far. In other words, once the high frequency content of the display has been reduced enough to effectively eliminate activity in the sustained channels, the duration of persistence should reflect only transient activity. Reducing spatial frequencies further should not have any effect on the duration of persistence. However, as Coltheart (in press) has pointed out, transient channels are probably not capable of carrying sufficient pattern information to allow accurate performance on a temporal integration task. A study by Carpenter and Ganz (1972) suggests that the minimum persistence for a given task depends on the highest spatial frequency information required to perform that task. If the task is one which involves making a judgement based on pattern information, it may be the case that the minimum persistence will depend on the sustained channel responding to the highest spatial frequencies necessary for accurate performance. If the spatial frequencies required to do the task are higher than those which would activate transient channels alone, then the results of Carpenter and Ganz (1972) would lead one to expect persistence to decrease to a minimum determined by those frequencies and asymptote at that value. This is in fact what Meyer and Maquire (1977) demonstrated in their study on the detection of pattern continuity. Their results indicate a minimum persistence of 300 msec on average for gratings of 2 c/d or less. However, these results can also be explained in terms of the probability hypothesis mentioned earlier. A more interesting case is the situation where the highest spatial frequencies required to perform a task are lower than those which would activate transient

channels alone. In this case, the sustained-transient explanation of persistence might lead one to expect that persistence should asymptote at a minimum duration which reflects transient activity. But, if Coltheart (in press) is correct in suggesting that sustained activity is necessary for accurate performance on a temporal integration task, then the task should become impossible to do before a minimum asymptote in the duration of persistence is reached. This is what occurred in the present study. Both Conditions -4D and -6D should have reduced the highest frequencies of the display to 2 c/d or less (see Table 1). If the results were to reflect the same minimum persistence demonstrated by Meyer and Maguire (1977), one might expect the curves for these two conditions to overlap, indicating an asymptotic value. However, for most subjects, this did not occur. Persistence continued to decrease beyond the -4D level of defocusing. In fact, as mentioned previously, it would appear that the task would become impossible to do at any plotting interval if the matrix had been defocused any further. If it can be assumed that this task represents one in which the maximum spatial frequency required for accurate performance is in fact below the point at which the sustained channels are extensively activated, then the results of this study cannot be explained in terms of the sustained-transient hypothesis of visible persistence.

It is possible that the reduction in persistence is not due to a reduction in sustained channel activity per se in relation to transient activity. It might be due instead to a reduction in the relative activity within sustained channels. Channels tuned to different ranges of spatial frequency have been shown by both psychophysical methods (Blakemore & Campbell, 1969), and neurophysiological methods (Campbell, Cooper, &

Enroth-Cugell, 1969; Maffei & Fiorentini, 1973). Thus, it is possible that the reduction in high frequencies caused a decrease in the activity of sustained channels responding to very high frequencies, while sustained channels responding to lower frequencies were not affected. Breitmeyer and Ganz's critical duration study (1977) definitely demonstrates a continuum of persistence durations over spatial frequency. This could be interpreted as indicating the existence of a series of sustained channels, each with a characteristic persistence. Thus, the gradual change in duration of persistence seen in this study could be explained by proposing that each increase in the level of defocusing knocked out more of the long persistence high frequency channels.

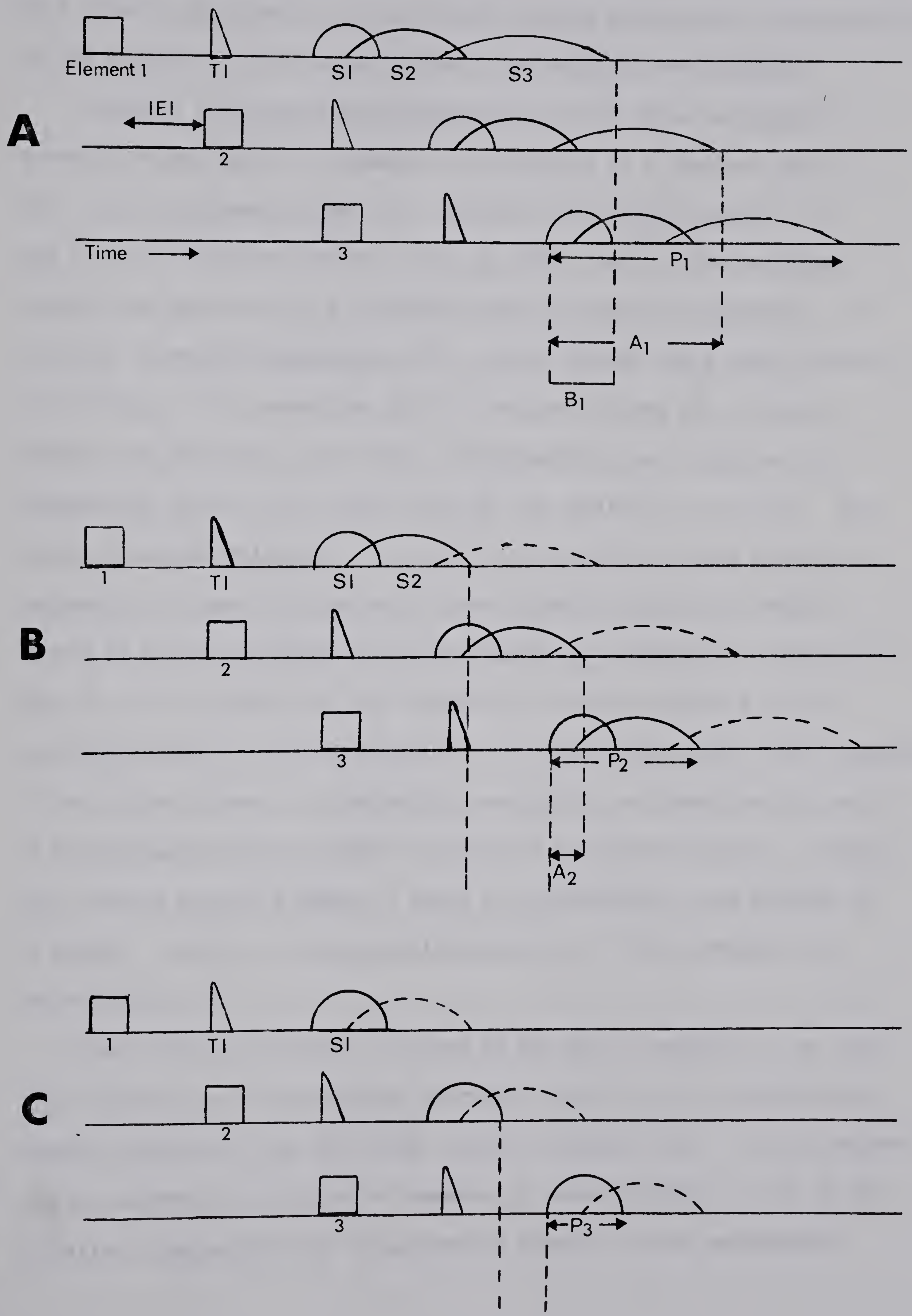
This explanation of the results fits very well with a theoretical description of sustained and transient channels presented by Breitmeyer and Ganz in 1976 to explain the shape of the two masking functions. They suggested that the results of the masking literature could be accounted for by hypothesizing the existence of several types of response to the same visual information. To this end, they proposed that the two basic types of channels, sustained and transient, are each responding to the visual information, and interacting with each other to produce masking effects. They propose further that there are at least three separate types of sustained channels, each responding to a different range of spatial frequency. According to their model, the latency of response and duration of activity vary directly with the range of frequency which activates the channel, while the amplitude of response is inversely related. For instance, the very high frequency channels have the longest latency and duration of activity and the smallest amplitude of response. Breitmeyer and Ganz's (1976) model also assumes that there is only one type of

transient channel with a short latency, short duration, high amplitude response.

From this model, it is predicted that persistence will depend on the channel responding with the longest latency and duration; that is, the channel responding to the highest frequencies in the display. As high frequency information is removed from the display, the very high frequency channels will not be activated, reducing the persistence of the display. As more high frequency information is removed, channels with shorter latencies and durations of activity will also be knocked out, causing a further reduction in visible persistence.

Figure 8 is a diagrammatic representation of this process. From the description of sustained channels given by Breitmeyer and Ganz, it would appear that visible persistence depends on both the latency and duration of activation within each sustained channel. Di Lollo (in press (a)) and Coltheart (in press) have suggested that persistence depends on the time required to process visual information to a particular level. If it can be assumed that the duration of processing time refers to the duration of activity within a set of channels relaying information about the display, then there is no fundamental disagreement between these two definitions. From this point, there are two alternatives for defining the duration of visible persistence for this model. One possibility would be that information in the transient channels would be combined with information in the sustained channels to yield a temporally integrated perceptual representation of the display. However, the effect of transient activity on visible persistence is not really under consideration here. In this study, the temporal aspects of the presentation remained constant while spatial frequency content was varied. Thus, the duration and

Figure 8. A diagramatic representation of the time course of transient and sustained channels activated by the successive presentation of three elements. (After Breitmeyer and Ganz, 1976.) Dotted curves represent channels in which activity has been reduced below threshold value for persistence.


A
Element 1
TI
SI
S2
S3
IEI
2
3
Time
P1
A1
B1
B
1
TI
SI
S2
2
3
P2
A2
C
1
TI
SI
2
3
P3

latency of transient activity should be unaffected by the manipulation. As a result, the duration of persistence can be defined more conservatively as the duration of processing within a set of sustained channels.

Figure 8 illustrates the presentation of any three successive elements in the matrix. Elements are separated by a temporal gap, IEI. Each displayed element will activate a transient channel (T1) and a set of sustained channels (S1, S2, S3). Each of the sustained channels is sensitive to a different range of spatial frequencies. S1 responds to medium frequencies with a short latency and a short duration of activity. S2 is sensitive to high frequencies and has a longer latency and duration of activity. S3 responds to very high spatial frequencies and has the longest latency and duration of activity. The three situations diagrammed in Figure 8 represent different amounts of defocusing. Figure 8A represents normal viewing conditions, while Figure 8B and 8C represent increasing levels of defocusing. Persistence (P1, P2, P3) is defined as the duration of activity within a set of sustained channels from the onset of S1 to the offset of S3. The probability of seeing two elements as temporally overlapping increases as the period of simultaneous activity within two sets of sustained channels increases. This overlap between elements 2 and 3 is represented in the diagram as A1 and A2. Overlap of the persistence among all three elements is represented as B1.

When channel activity in Figure 8A and 8B is compared, it is clear that the duration of persistence decreases from P1 to P2 as defocusing reduces activity in the very high frequency channel (S3). As the temporal overlap between two successive elements is reduced from A1 to A2 in this situation, the probability of successive elements being perceptually

integrated is reduced. It should also be noted that there is no longer any overlap between the first and third elements, hence they should appear successive to the subject. It is obvious that, in order to maintain the same temporal overlap as seen in Figure 8A, the IEI would have to be reduced. In terms of the paradigm used in this study, this would mean that the entire matrix would have to be presented at a shorter plotting interval in order to be temporally integrated by a subject. When the defocusing is increased (Figure 8C), activity in the high frequency channel (S2) is reduced, further reducing the persistence to P3 and eliminating any overlap between the persistence of any of the three elements. In this case, the three elements would appear successive to the subject.

From this diagram, it can be seen that visible persistence would decrease gradually as the channels with longer latency, longer duration characteristics are not activated by the visual information in the display.

There are two important assumptions in the present model for visible persistence. The first is that persistence depends on relative activity in a set of sustained channels. The second assumption is that the model suggests there are two factors involved in determining the duration of persistence: latency and duration of activity within a channel. But is it possible to separate out the effect of these two factors? There is evidence from the neurophysiological literature which indicates that there are latency differences within the set of sustained-type cells which might depend on spatial frequency. Cleland, Levick, Morstyn and Wagner (1976) have classified cells in the lateral geniculate nucleus (LGN) and visual cortex of the cat as having sustained and transient characteristics. They recorded the latencies of these cells to electrical

stimulation of the retinal complex and found that there were a number of sustained cells that responded with longer latencies than expected. At the LGN, latencies varied from two to 12 msec, while at the cortex, they varied from four to 20 msec. Dow (1974) showed the same kind of continuum in latency in recordings from the visual cortex of monkeys. He found that sustained cells with complex receptive field characteristics had longer latencies than those with less well-defined receptive fields. It may be that these latter cells would respond to lower spatial frequencies than the cells with more complex receptive fields and longer latencies. At any rate, it does not appear that all sustained cells respond with the same latency at the cortical level.

Some of the studies mentioned earlier may bear on the question of latency. For instance, the reaction-time studies (Vassilev & Mitov, 1976; Breitmeyer, 1975) might be interpreted as measuring latency differences, as opposed to persistence per se. Reaction-time is often thought of as a measure of the latency of processing to the point of decision-making. Thus, the important variable in these studies might have been the latency from onset of the stimulus to onset of the highest frequency channel. If this is the case, then one could interpret the difference between a latency of 200 msec for a grating of 0.5 c/d and a latency of 350 msec for 16 c/d as showing a 150 msec difference in the latency of the highest frequency channels activated by these two gratings.

As far as the duration of activity is concerned, the neurophysiological evidence necessary to support this contention is not available. However, a reconsideration of Breitmeyer and Ganz's (1977) critical duration

experiment may be useful. The critical duration for the summation of intensity is most likely not determined by latency, but by the duration of processing within a given sustained channel. Thus, a difference between a critical duration of 60 msec for a 0.5 c/d grating and a critical duration of 200 msec for a 16 c/d grating might be interpreted as a difference in 140 msec in the duration of activity in the channels involved. As these studies were not originally designed to partial out the effect of these factors, more research must be conducted in this area to demonstrate the validity of Breitmeyer and Ganz's description of the system. However, it would appear that, so far, all the data provides some measure of support for this hypothesis. In addition, the gradual change in persistence instituted by varying spatial frequency and the lack of a minimum asymptote would seem difficult to explain in terms of a simpler hypothesis of relative activity in sustained and transient channels.

Some Methodological Considerations

There are several points that should be mentioned in conjunction with the defocusing procedure which may have affected the results. First of all, defocusing caused a slight reduction in image size due to the angular magnification factor associated with each lens value. The values for this factor are given in Table 1. It can be seen that the reduction is small (from one to three percent). However, if the size reduction had any effect, it would have decreased, rather than increased, the effect of defocusing in persistence.

Defocusing the image of the display produced a blur circle on the retina for every point of light in the display, causing a more even

distribution of light on the incident area of the retina. Thus, the luminance at any point on the retina was reduced, resulting in a corresponding reduction in the apparent brightness of the display. While this reduction was slight, it may have affected the persistence of the display. One might expect, however, from other work done in the area of temporal integration (Efron, 1970a,c; Haber & Standing, 1969, 1970; Allport, 1970), that a reduction in intensity would cause an increase in persistence and reduce, not increase, differences seen in the results. To ensure that luminance was not confounded with reduction of spatial frequency, conditions were run to investigate the effect of reduced brightness on persistence in this task. Surprisingly, as Figures 5, 6 and 7 demonstrate, the only effect reduced brightness appeared to have was to make the overall task of locating the missing element more difficult at all plotting intervals. The reductions in intensity level were much larger than those caused by the defocusing lenses, according to the subject's reports. In fact, these reduced intensity levels were in the scotopic range, as subjects required 10 minutes adaptation to do the task at all, and they reported reduced brightness in the foveated area of the display. This may, in part, account for the high rate of errors at all plotting intervals. At any rate, it is clear that the brightness reduction caused by defocusing is not responsible for the reduction in persistence which coincided with the increase in defocusing.

The fact that reduced brightness did not increase persistence as expected, is interesting in itself. It may be that the temporal integration task used in this experiment is inherently different from the judgement of synchronicity and phenomenal continuity tasks that have been used to

examine the relationship between intensity and duration of persistence. This question merits further careful investigation and is under study in our laboratory at the moment.

Conclusions

In conclusion, it can be said that visible persistence depends on spatial frequency. While this study does not test the hypothesis, it does provide some indirect support for Breitmeyer and Ganz's suggestion that there may be a number of sustained channels involved in the processing of information. It seems likely that the variation of visible persistence with spatial frequency may be a result of relative processing in the sustained channels, as opposed to the relation of activity between the sustained and transient channels.

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Appendix 1

Calculation of Highest Resolvable Spatial Frequency

The radius of the blur circle was calculated as follows. The image distance (v_2) of the compound lens system (i.e. the eye system and defocusing lens) was calculated using Ogle's (1968) formula.

$$v_2 = \frac{u_1(1-F_1 s)+s}{u_1(F_1+F_2-F_1F_2 s)-(1-F_2 s)}$$

Where u_1 is the distance from the display to the defocusing lens, F_1 is the power (in diopters) of the defocusing lens, s is the distance between the defocusing lens and the principle point of the reduced schematic eye (Ogle, 1968), and F_2 is the power of the eye in diopters.

This value for v_2 was then compared with the length of the emmetropic eye from the nodal point to the retina (17 mm). The resulting difference (x) gives the distance behind the retina at which the image would have been in focus.

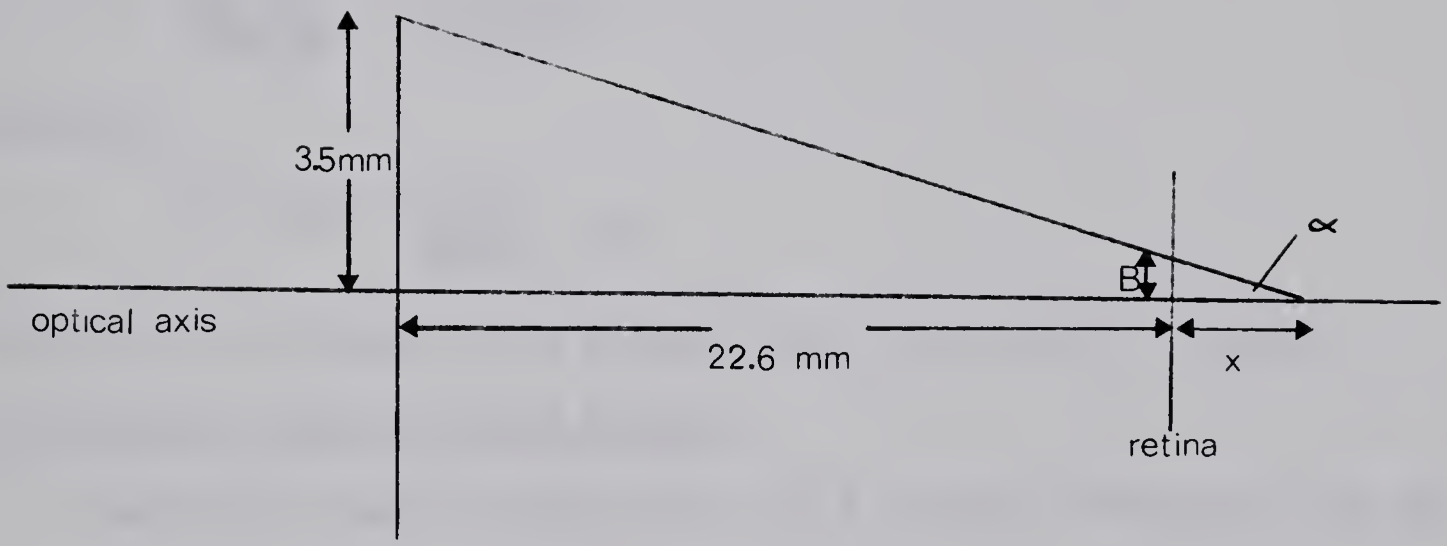
Figure 1.1 shows how this distance, x, can be used to determine the radius of the blur circle as produced by a given entrance pupil. A maximum pupil diameter (7 mm) was used in these calculations, as subjects were seated in a darkened chamber. The emmetropic length of the impinging cone of light was based on the distance from the retina to the principle plane of the lens.

The trignometric relationship between the blur radius (B) and the pupil radius is as follows:

$$\tan\infty = \frac{B}{x} = \frac{3.5\ \text{mm}}{(22.6+x)\text{mm}} \quad ;$$

[illegible]

Figure 1.1. An illustration of the trigonometric ratio for deriving the radius of the blur circle, B.


3.5mm
∝
B
optical axis
22.6 mm
x
retina

therefore,

$$B=\frac{3.5x}{(22.6+x)} \text{ mm.}$$

Using Raliegh's criterion that the resolvable distance on the retina is equal to the radius of the blur circle (B), the values derived for B may be translated into spatial frequency. However, it is generally acknowledged that visual discrimination is usually somewhat better than Raliegh's criterion predicts (Longhurst, 1957). To get around this difficulty, a ratio formula was used. It is known that the normal eye can resolve a difference in position of 0.0166° (60 c/d). This corresponds to a distance of .005 mm on the retina. Thus a ratio can be constructed as follows:

$$\frac{60 \text{ c/d}}{.005 \text{ mm}} = \frac{\text{SF (c/d)}}{\text{B (mm)}} \quad .$$

Therefore,

$$\text{SF (c/d)} = \frac{B(60)}{.005} \text{ c/d} \quad ,$$

where SF c/d is equal to the highest resolvable spatial frequency.

Calculation of Magnification Factors

The angular magnification factor (A_o) for each defocusing lens was calculated using Ogle's (1968) formula.

$$A_o = 1+hF \quad ,$$

where h is the distance from the defocusing lens to the cornea, and F is the power of the defocusing lens in diopters.

Appendix 2

Calculation of the Values in Table 2

The values in Table 2 were obtained as follows. The data points bracketing the 50 percent error level were first-order digitally smoothed (Dawson & Doddington, 1973) to ensure that the values would reflect differences of a continuous function rather than statistical variation in particular points. The digital smoothing consisted of calculating a weighted (.25, .50, .25) average based on three successive points on the curve. The plotting interval for 50 percent error was estimated by linear interpolation from these values. For Condition OD, some of the curves did not reach the 50 percent level. In these cases, the plotting interval was given as >160 msec. In the analysis of variance, these values have been under-estimated as 160 msec.

Appendix 3

Analysis of Variance

Factor	DF	SS	MS	F	p
Subjects	3	2812.52	937.51		
Defocusing	3	22419.71	7473.24	40.85	< .01
Subjects X Defocusing	9	1646.39	182.93		
Mode	1	19281.57	19281.57	292.77	< .01
Subjects X Mode	3	197.59	65.86		
Defocusing X Mode	3	839.65	279.88	4.91	N.S.
Subjects X Defocusing X Mode	9	513.06	57.01		
Total	31	47710.49			

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